Minneapolis, Minnesota
NOISE-CON 2005
2005 October 17-19

Effect of Discharge Duct Geometry on Centrifugal Fan Performance and Noise Emission

David Nelson
Nelson Acoustics
PO Box 879
Elgin
TX 78621-0879
david@nelsonacoustical.com

William Butrymowicz
Chris Thomas
Orbital Technologies Corp.
1212 Fourier Dr.
Madison
WI 53717-1961

ABSTRACT
Non-ideal inlet and discharge duct geometries can cause significant changes to both the aerodynamic performance ("fan curve") and specific sound power emission of a fan. A proper understanding of actual installed performance, as well as a good estimate of the system backpressure curve, is critical to achieving flow and acoustic goals as well as other criteria such as power consumption, mass and volume. To this end a battery of ISO 10302 tests was performed on a blower assembly which supports the Advanced Animal Habitat, being developed by Orbital Technologies Corp. (ORBITEC) for deployment on the International Space Station. The blower assembly consists of four identical centrifugal fans that, among themselves and across two prototypes, incorporated several discharge geometries. The inlet geometries were identical in all cases. By comparing the dimensionless pressure-flow and noise emission characteristics across the cases, significant insight into the nature and potential magnitude of these effects is gained.

1. INTRODUCTION
Comprehensive engineering information on fans is all but nonexistent. While a fan curve and a single sound pressure level reading is better than nothing, it is insufficient for performing the early stage design work so critical for achieving a successful low-noise design. Catalog data applies only to ideal flow conditions which seldom exist in practice. Fan systems designed on this basis often deliver insufficient flow, spin too fast, consume too much power, and make too much noise. Worst of all, the rest of the design is likely to have crystallized before the shortfall is noticed. This paper describes the motivation, methods and results of an effort to obtain the needed engineering information for use in early design stages. It documents the strong effect of non-ideal outlet geometries on the fan curve and noise emission of the installed fan.

NASA has established stringent requirements for noise emission from experimental payloads on the International Space Station [1], along with requirements for documented noise control work in early design stages and compliance verification tests prior to acceptance. ORBITEC has aggressively incorporated noise control into its design efforts for the Advanced Animal Habitat (AAH). Thermal cooling and noise control design progressed in parallel, and a noise emission model was developed which permits review of the noise emission consequences of later design modifications. The accuracy of the model, and the ultimate compliance with the criterion, hinges on an accurate understanding of the airflow delivery and noise emission of the Blower Assembly *as installed*.

2. BACKGROUND

The AAH Blower Assembly (see Figure 1 below) consists of four EBM Papst REF100-11/12 100 mm diameter centrifugal fans and a flow-directing insert. Two fans recirculate air across temperature control fins which condition the air within the Specimen Volume, home to a number of rats during the flight. The two remaining fans exchange air with the cabin. Both the Recirculation Fans and the Exchange Fans are presented with significant flow resistances in the form of constrained duct geometries and various filters that control dust, waste and odors.

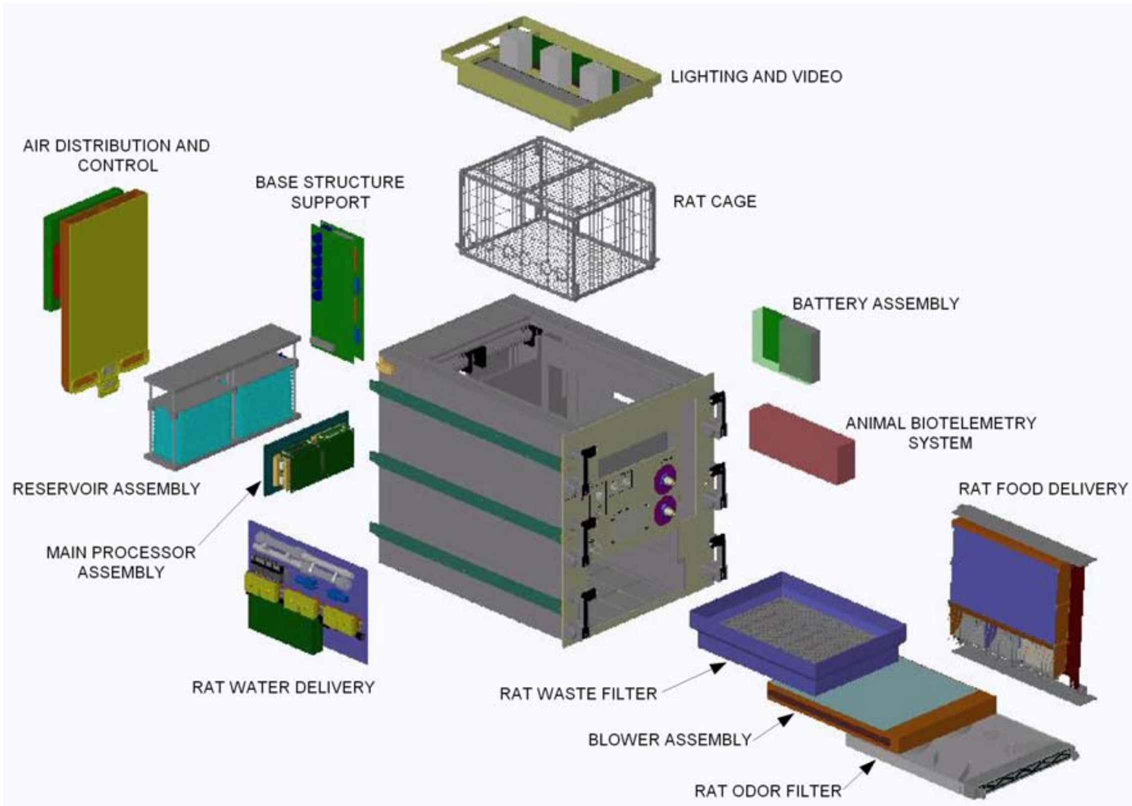

Figure 1: AAH Exploded Subsystems Diagram

The Blower Assembly as tested incorporates a melamine foam insert which serves as both sound absorber and internal ductwork. Volume constraints required some less-than-ideal flow constrictions within the Blower Assembly. The Recirculation Fans have independent outlets which are dissimilar. The Exchange Fans discharge into a common duct. During the tests the Recirculation and Exchange Fans were operated singly or as pairs, using both the Original and a Revised foam insert. The resulting data set offers a rare opportunity to evaluate a number of discharge duct geometries applied to one type of fan.

Simultaneous airflow and noise emission tests of the Blower Assembly were conducted in accordance with ISO 10302 [2]. Flow and noise data were collapsed to non-dimensional form using Fan Similarity Laws [3] as:

$$
\begin{aligned}
\phi &= Q \big/ ND^3 \\
\psi &= P_S \big/ \rho N^2 D^2 \\
\lambda &= W_E \big/ \rho N^3 D^5 \\
K_{WA} &= L_{WA} - \log(Q P_S{}^2) \quad ,
\end{aligned}
\tag{1}
$$

where the non-dimensional quantities are the flow coefficient ϕ, pressure coefficient ψ, and power coefficient λ. Corresponding dimensional quantities are flow rate Q, static pressure rise P_S, electrical power consumption W_E, A-weighted sound power level L_{WA} in Bels, atmospheric density ρ, rotation rate N and impeller diameter D. Consistent units must be used in the computation of these quantities. K_{WA}, the specific sound power level, is handled as if it were non-dimensional although its value depends on the system of units chosen. For the purposes of this paper, K_{WA} is computed using the convention of flow rate in cubic feet per minute and static pressure rise in inches of water, as is customary in the USA.

Estimates of element resistances were developed by ORBITEC and incorporated into model system characteristics to assess flow and noise emission for any operating point of interest.

A. Test Conditions

A sketch of the insert is given below in Figure 2. The Original insert was machined from melamine foam using commercial off-the-shelf (COTS) tooling and conventional machining methods. The Revised insert was hand-cut and incorporated an increased relief area around the Exchange Fan impellers (dashed line) and was more effectively sealed to reduce leakage. The "scroll" shape for the left Recirculation fan was also modified to match the right fan, but this configuration could not be tested because the new discharge opening did not line up with the existing opening in the shell.

The fans are designated Left and Right as viewed from above facing the Discharge. The Right fans tended to produce more flow because the shape of the foam insert cooperated better with the direction of flow caused by the impeller rotation. The fans rotate in a clockwise sense when viewed from above.

The tests documented in this paper cover the cases shown in Table 1. The area at the Blower Assembly Discharge is tabulated as a percentage of the impeller inlet area (excluding the hub).

B. ISO 10302 Test Method

The ISO 10302 Test Method involves the installation of the fan on an acoustically transparent plenum incorporating a variable flow resistance. The fan plenum [4] used for the tests (see Figure 3) permits simultaneous control of the variable resistance slider and measurement of static pressure, rotation rate, voltage, current, and sound power using LabVIEW™-based software. The plenum has been calibrated so that the flow can be computed from the static pressure and the slider position. This allows for rapid testing of the fans and permits large numbers of operating points to be rapidly evaluated.

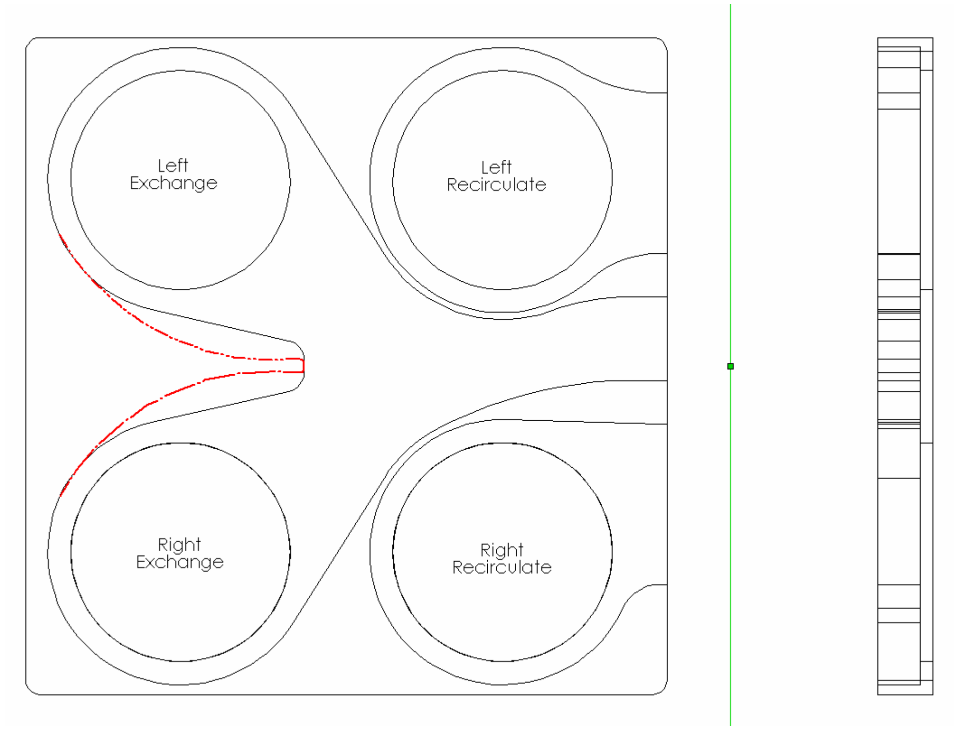

Figure 2: Plan and elevation view of Blower Assembly foam insert. The approximate locations of additional cutouts for the Revised insert are indicated with dashed lines.

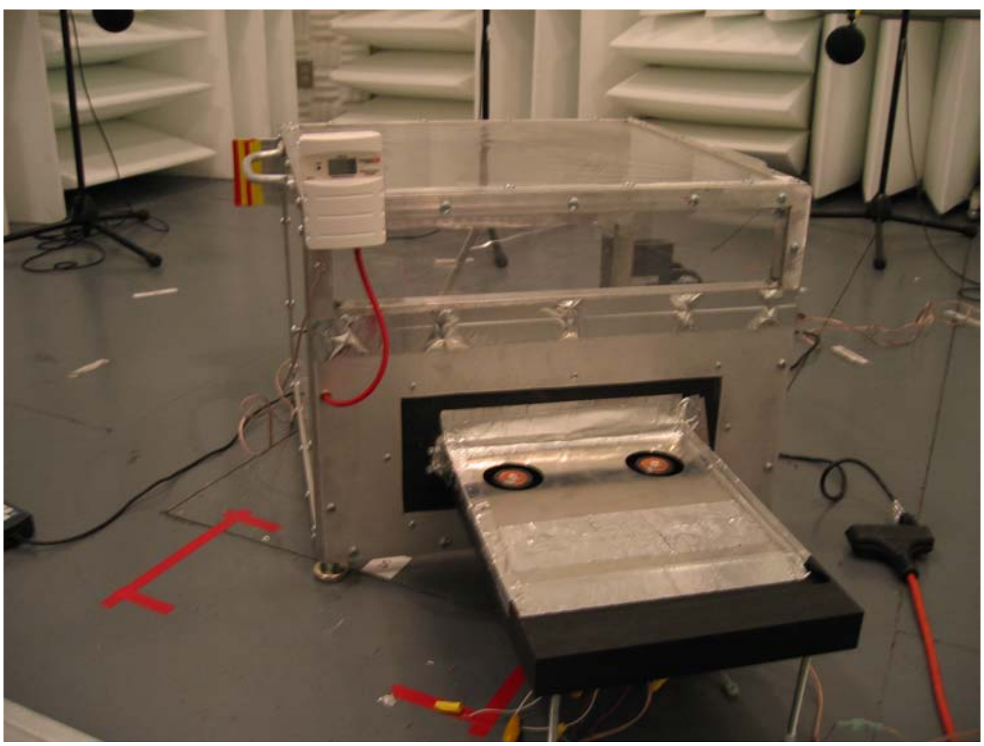

Figure 3: Blower Assembly mounted on ISO 10302 Fan Test Plenum.

Table 1: Test Cases

	Original or Revised Insert	Outlet Area as Percentage of Impeller Inlet Area
Average of Two Exchange Fans	Original	15%
Left Exchange Fan	Revised	31%
Right Exchange Fan	Revised	31%
Average of Two Recirculation Fans	Original	60%
Right Recirculation Fan	Revised	60%

3. LABORATORY MEASUREMENTS

A. Fan Curves vs. Exit Geometry

Non-dimensional fan curves for various exit geometries are charted below in Figure 4. Only data related to 12V operation have been used in order to simplify the plots (slight differences are observed). Where two fans operated in parallel, the flow coefficient has been halved so that all the comparisons are referenced to a single fan. The expected catalog performance is in red and a system characteristic (for the recirculation fans) is represented by the dashed green line.

Both the flow and pressure are considerably reduced relative to catalog performance, trending with the percentage of discharge flow area relative to the inlet. This is a consequence both of internal resistances within the flow passages and flow distortions within the fan. It is now possible to more accurately assess the actual flow that will be delivered and the speed necessary to achieve a desired flow.

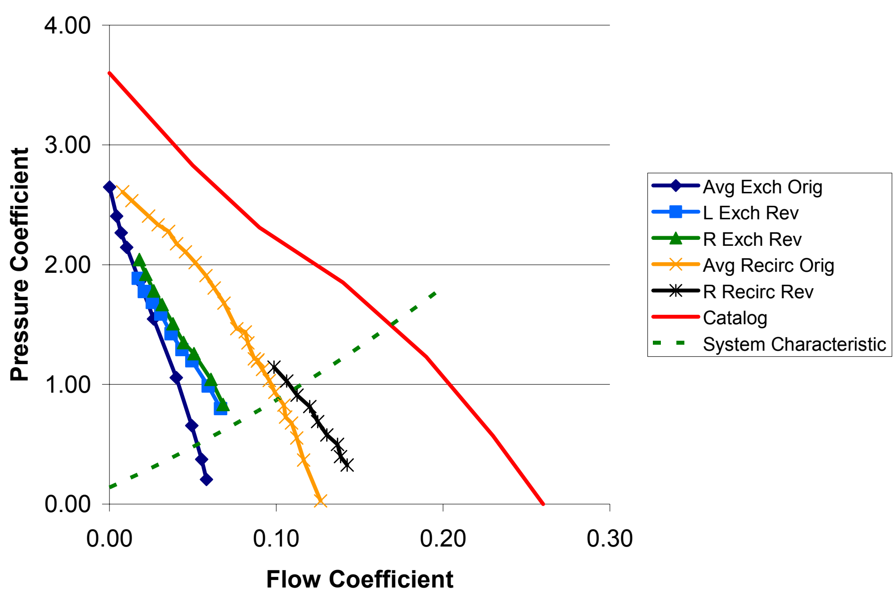

Figure 4: Non-dimensional fan curves for various exit geometries, compared to catalog data and a system characteristic.

From Figure 4 it is evident that, based on catalog data, the expected operating point for a Recirculation fan would have been near (ϕ=0.16, ψ=1.40). However, installed in the Blower Assembly with the Revised insert, the right Recirculation fan would be expected to operate near (ϕ=0.12, ψ=0.90). In other words, a 25% reduction in flow is anticipated for any given speed relative to catalog data. To make up for the loss, the designer has the option of improving the flow in the Blower Assembly, reducing the system resistance, or increasing the fan speed 33%. Obviously the two former options are preferred for low-noise design.

Note that the Exchange fans deliver increased flow using the Revised insert, probably as a combined result of the increased passage size and reduced leakage. The right fan slightly outperforms the left fan because the shape of the passageway cooperates better with the rotational sense of the impeller. The right Recirculation fan outperforms the left for the same reason. The scroll shape for this fan did not change during the transition to the Revised insert, so the superior performance may also be due in part to reduced leakage.

B. Specific Sound Power Level Curves vs. Exit Geometry

The computation of K_{WA} suffers from a well-known shortcoming: the noise emission is assumed to vary as $\phi\psi^2$, which would mean that there can be no noise emitted at free air or shut-off. Since this is clearly not the case, K_{WA} values have a tendency to increase strongly at either end of the chart. Only data related to 12V operation have been used in order to simplify the plots. Where two fans operated in parallel, 0.3B has been subtracted from the total for both so that all data is referenced to a single fan.

1. K_{WA} vs. Flow Coefficient

When plotted versus Flow Coefficient (see Figure 5) the chart is somewhat chaotic because the range of flows for the various curves differs significantly. The catalog data is of dubious value because the manufacturer reports only a single sound pressure level figure, from which a sound power level has been estimated and applied for all operating points.

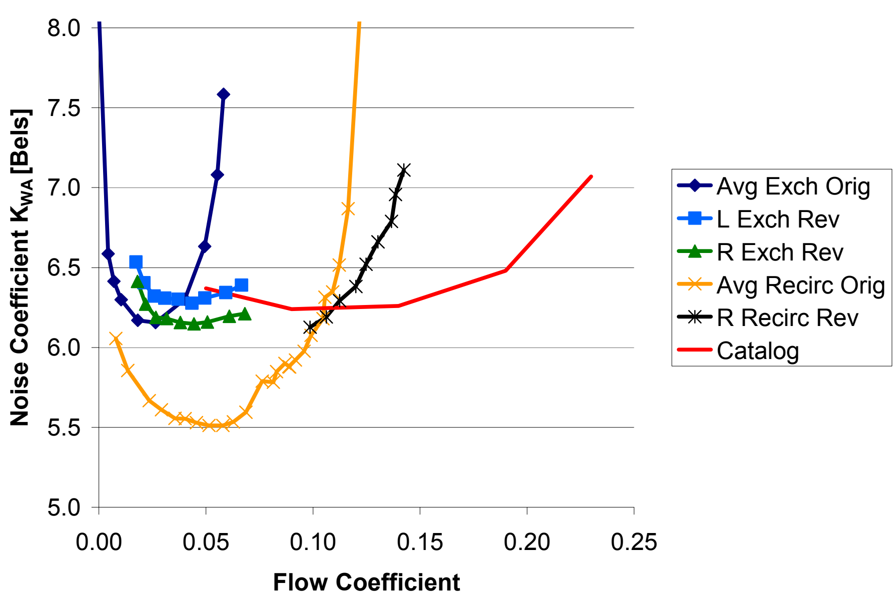

Figure 5: Specific sound power level curves vs. flow coefficient for various exit geometries, compared to catalog data.

While a clear pattern does not emerge, it is evident that the Revised insert consistently brings about reduced noise emission. Furthermore, the Recirculation Fans are as much as 5 dBA quieter than the Exchange Fans. Finally, the right Exchange fan appears to be about 1 dB quieter than its counterpart.

2. K_{WA} vs. Pressure Coefficient

When plotted versus Pressure Coefficient (Figure 6) the chart is dramatically more coherent, offering better hope of one day modeling this type of data.

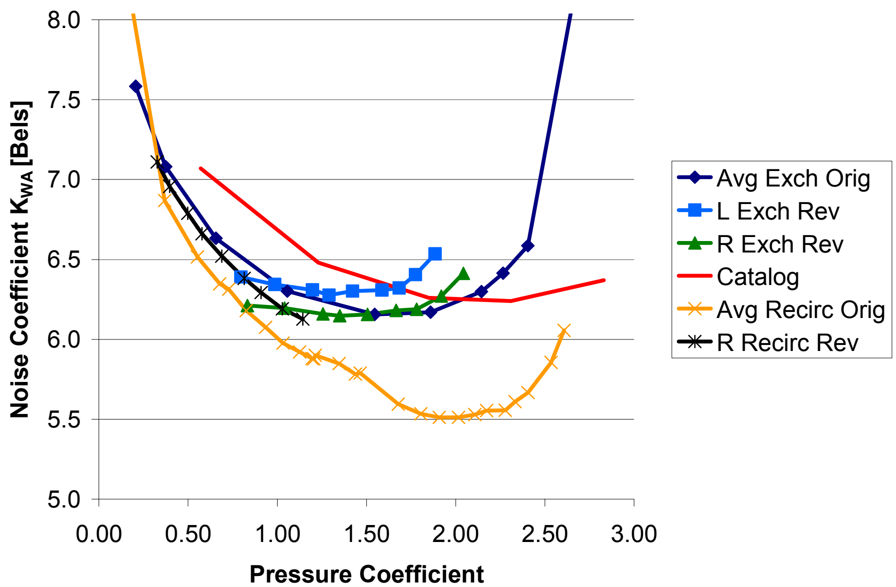

Figure 6: Specific sound power level curves vs. pressure coefficient for various exit geometries, compared to catalog data.

It seems odd that for many operating points the fans with Revised insert appear to be slightly noisier than with the Original insert, especially since this did not seem to be the case in Figure 5. This is most likely a consequence of the U-shape of the K_{WA} curves in conjunction with the fact that their points of minimum noise output fall at different operating points. It is also possible that the hand-cut Revised insert increased turbulence somewhat. However, the general similarity of the curves suggests that noise emission correlates better with the pressure coefficient than with the flow coefficient.

4. CONCLUSIONS

Installed fans cannot be expected to perform as catalog data would indicate. Inflow and outflow distortions cause them to behave differently in an aerodynamic sense, which is manifested in changes to the fan curve and specific sound power level curve. The effect of various candidate inlet and outlet geometries on fan performance should be measured early in the design process in order to provide realistic estimates of installed flow and noise emission. Because the changes can be significant, this type of information is indispensable to a low-noise design effort.

A long term goal of Nelson Acoustics is to collect performance data from many tests representing ideal and installed conditions, and then to develop a model and a database of factors for converting catalog data to an engineering estimate of installed performance.

ACKNOWLEDGEMENTS

The measurement component of this work was funded by ORBITEC through NASA Ames Research Center under contract number NNA05-C-P09C. The contributions of Jeff Schmitt of ViAcoustics and John Phillips of Acoustic Systems to the development of the automated fan test plenum are greatly appreciated. Finally, thanks are due to Beth Cooper and Dennis Huff of NASA Glenn Research Center, aeroacoustic consultant Eugene Krejsa, Eric Phillips of Boeing Payload Engineering and Integration, and Jerry Goodman and Christopher Allen of NASA Johnson Research Center for their encouragement in the pursuit of low-noise spaceflight hardware designs and for valuable technical discussions regarding fan noise.

REFERENCES

[1] *Pressurized Payloads Interface Requirements Document, International Space Station Program*, SSP 57000, Revision B, Including PIRN 0062 (NASA Johnson Space Center, May 1998).

[2] *Acoustics – Measurement of airborne noise and structure-borne vibration of small air moving devices*, International Standard ISO 10302:1996 and current committee drafts (International Organization for Standardization, Geneva, Switzerland, 1996).

[3] Robert Jorgensen, Ed., *Fan Engineering, Eighth Edition* (Buffalo Forge Company, Buffalo, New York, 1983).

[4] Jeff G. Schmitt, David A. Nelson, John Phillips, "An Automated System for the Acoustic and Aerodynamic Characterization of Air Moving Devices" *Proceedings of Noise-Con 2005*, (2005).